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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 10-87

EVALUATION OF AN IMPULSE NOISE PRODUCING UNDERWATER EXPLOSIVE DEVICE ON HEARING IN DIVERS

By:

NAVY EXPERIMENTAL DIVING UNIT

(6)

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407-5001

IN REPLY REFER TO:

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By:

LT J. A. STERBA, MC, USNR

JULY 1987

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

AD-A185 728

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NEDU REPORT NO. 10-87	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EVALUATION OF AN IMPULSE NOISE PRODUCING UNDERWATER EXPLOSIVE DEVICE ON HEARING IN DIVERS.		5. TYPE OF REPORT & PERIOD COVERED FINAL 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) LT J. A. STERBA, MC, USNR		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS NAVY EXPERIMENTAL DIVING UNIT PANAMA CITY, FL 32407-5001		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE JULY 1987 13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this Report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A: Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

NAVSEA TASK NO. 87-26
NEDU Test Plan No. 87-13
Impulse Noise
Sound Pressure Level
Temporary Threshold Shift
Audiogram
Underwater Hearing
Underwater Explosions

20. ABSTRACT (continue on reverse side if necessary and identify by block number)

The diver Audible Recall Device (A.R.D.) is a self-contained small explosive device designed with a 6.6 sec delay fuse ignited by pulling a lanyard. It is weighted by both sand and lead shot, allowing detonation approximately 3m (9.8 ft) underwater. At a distance of 7m (22.9 ft) from the device, detonating at 3m (9.8 ft) underwater, the peak sound pressure level (SPL) is 185.5 dB (re 20 uPa) in-water, equivalent to 5.44 psi. With a explosion duration of 1.0 msec, the impulse is 2 psi·msec. Five U.S. Navy divers were exposed to this R.A.D. at a peak SPL of 186.2 dB (re 20 uPa) in-water, equivalent to an in-air value of 151.2 dB, which is 11.2 dB over the current 140 dB safe exposure limit for impulse noise, in-air, established by OPNAVINST 5100.23B [18103a(4)]. No reduction in hearing sensitivity in all five diver-subjects was observed
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S/N 0102-LF-014-6601

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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20. (Continued)

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GLOSSARY

A.R.D.	Audible Recall Device
c	velocity of sound
dB	decibel
ft	foot
Hz	Hertz or cycles per second
m	meter
NAVMEDCOMINST	Naval Medical Command Instruction
NAVSEA	Naval Sea Systems Command
NCSC	Naval Coastal Systems Center
NEDU	Navy Experimental Diving Unit
NSWC	Naval Surface Weapon Center
p	density of water
Pm	measured sound pressure
P_{ref}	referenced sound pressure
psi	pounds per square inch
(re 20 uPa)	sound pressure has been referenced to 20 uPa
SCUBA	Self Contained Underwater Breathing Apparatus
SD	Standard Deviation
SPL	Sound Pressure Level
SPL_{air}	Sound Pressure Level measured in air
SPL_{water}	Sound Pressure Level measured in water
TTS	Temporary Threshold Shift
uPa	Micro Pascals
yd	yard
Z	Impedance of water

ABSTRACT

The diver Audible Recall Device (A.R.D.) is a self-contained small explosive device designed with a 6.6 sec delay fuse ignited by pulling a lanyard. It is weighted by both sand and lead shot, allowing detonation approximately 3m (9.8 ft) underwater. At a distance of 7m (22.9 ft) from the device, detonating at 3m (9.8 ft) underwater, the peak sound pressure level (SPL) is 185.5 dB (re 20 uPa) in-water, equivalent to 5.44 psi. With a explosion duration of 1.0 msec, the impulse is 2 psi•msec. Five U.S. Navy divers were exposed to this A.R.D. at a peak SPL of 186.2 dB (re 20 uPa) in-water, equivalent to an in-air value of 151.2 dB, which is 11.2 dB over the current 140 dB safe exposure limit for impulse noise, in-air, established by OPNAVINST 5100.23B [18103a(4)]. No reduction in hearing sensitivity in all five diver-subjects was observed as demonstrated by no temporary threshold shifts (TTS) in their audiograms. The impulse was described as very loud, but not uncomfortable. With the frequency of the A.R.D. impulse being 200-300 Hz, there was no damage to the lungs or gastrointestinal tract which would have been expected at lower frequencies around 50 Hz with higher impulse levels above 10 psi•msec. The A.R.D. was reliably heard by all five divers as far away as 1006m (1100 yds) at a depth of 3.0m (10 ft) in 9.1m (30 ft) of water. However, due to severe shrapnel risk from the casing, end-cap, and from lead shot and sand used as ballast, the A.R.D. was determined to be hazardous.

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EVALUATION OF IMPULSE NOISE PRODUCING
UNDERWATER EXPLOSIVE DEVICE ON HEARING IN DIVERS

By

LT J. A. Sterba, MC, USNR

I. INTRODUCTION

A. Effects of Impulse Noise on Divers' Hearing

The Navy Experimental Diving Unit (NEDU) has been tasked by Naval Sea Systems Command (NAVSEA) to test and evaluate the diver Audible Recall Device (A.R.D.) for safety, ease of use, and general user acceptability (1). The Navy Surface Weapon Center (NSWC) has recently conducted very favorable preliminary field testing of the A.R.D. compared to the currently used M-80 firecracker. In addition, NSWC has also successfully completed laboratory safety testing on the A.R.D. (2). However, the A.R.D. is an impulse noise producing underwater explosive device which may be hazardous to the diver's internal organs such as the inner ear hearing organ, known as the cochlea, the lungs and the gastrointestinal system. NEDU has recently completed the first human diving medical research project on the effect of underwater impulse noise on divers' hearing using a gun-powder actuated underwater tool (3). According to U.S. Navy safe exposure limits for impulse noise (4), divers tolerated slightly greater than 10 decibels (dB) above the safe exposure limit of impulse noise without any reduction in hearing sensitivity. The divers' hearing was assessed by standard audiometry with a reduction in hearing sensitivity being defined as a temporary threshold shift of 15 dB or greater on their audiograms.

For a complete evaluation of the effect of the A.R.D. on hearing, not only was the overall sound pressure level (SPL) of the A.R.D. needed, the frequency spectrum of the underwater impulse noise was also important. By this analysis during unmanned testing we were able to predict at which frequencies hearing damage might occur. Furthermore, we could predict whether there might be any pulmonary or gastrointestinal injury relying on both manned and unmanned research on safe distances from an underwater blast (5, 6).

According to NSWC (2) the M-80 firecracker has unofficially been used by the Sea Air Land (SEAL) divers to acoustically recall divers. However, the M-80 is difficult to use, is very unreliable and has safety and administrative problems. The proposed replacement, the A.R.D., is a hand-held explosive device using a 6.6 sec delay fuse activated by pulling a lanyard. This gives ample time to throw the device overboard into the water. The A.R.D. is weighted by both sand and lead shot allowing it to sink to approximately ten feet before explosion underwater.

The A.R.D. is produced by Propellex Corporation (Edwardsville, IL) and was recently field tested by the Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD (2). Although no underwater acoustic

measurements were reported, the A.R.D. was noted by SEAL diver-subjects to be louder and more easily heard from 200 to 400 yards compared to the M-80. Closer than 200 yards, the M-80 was observed to be louder. It was proposed by NSWC that due to the A.R.D.s long duration impulse compared to the short spike impulse of the M-80, the A.R.D.s signal could carry further underwater.

An international literature search using Index Medicus, the Undersea and Hyperbaric Medical Society and the Military National Technical Information System failed to uncover any research on the effects of the M-80 firecracker on diver's hearing or causing any injury. Anecdotal reports though have demonstrated that the M-80 can cause severe soft tissue damage if explosions occur while the M-80 is hand held.

In field testing at NSWC and recently at NEDU during offshore diving operations, there were no reports of the A.R.D. producing an uncomfortably loud explosion. Furthermore, there were no complaints of ringing of the ears (tinnitis), fullness or pain in the ears or any subjective reduction in hearing related to the use of the A.R.D.

According to current U.S. Navy instructions (4), the safe exposure limit to impulse noise is 140 dB which is an <u>in-air</u> value referenced to 20 micro pascals (re 20 uPa). As explained in detail in the Methods Section B, 140 dB <u>in-air</u> is equivalent to 175 dB <u>in-water</u> (re 20 uPa). The objectives of this project were to: (1) determine by unmanned testing, the distance from the A.R.D. that will produce the safe exposure limit of 175 dB in-water (re 20 uPa); (2) expose diver-subjects to the A.R.D. at this predetermined distance; (3) determine if there is any reduction in the divers' hearing sensitivity as measured by audiometry following exposure to the A.R.D. Any change of 15 dB or greater will be defined as a significant temporary threshold shift (TTS); (4) determine the safe distance where no TTS exists for all divers; (5) determine, off-shore, the maximum distance where all divers can reliably hear the A.R.D. To represent the noisiest and most acoustically muffled situation, divers breathed from SCUBA and wore either a ¼" or 3/16" thick neoprene hood. The degree of thickness of this wet suit hood does not affect the acoustic protection of the diver (3). The suit hood must completely cover the exposed forehead, thus limiting bone conduction of the underwater noise to allow 5-10 dB of acoustic protection (3).

B. Evaluation of Shrapnel Risk from the A.R.D.

Although NSWC has found no evidence for a risk from the lead shot in the A.R.D. acting as shrapnel, both surface and underwater tests were conducted at NEDU assessing this possible shrapnel risk. With a considerable amount of various materials surrounding the gun powder charge such as plastic, hardened glue, cardboard, rubber tubing as well as adjacent sand and lead shot, extreme caution was used while testing the A.R.D. out of water.

The A.R.D. sinks to approximately ten feet underwater due to it being negatively buoyant from both sand and lead shot. According to the engineering schematic diagram (Fig. 4, reference 7), the primer and audible output consisting of pistol gun powder does not have any sand or lead shot immediately surrounding the explosive end of the A.R.D. However, the sand and lead shot does surround the adjacent internal tube containing the fuse assembly which extends right up to the gun powder charge. Assuming that the explosion might travel the path of least resistance, it was predicted that the explosion might travel into the fuse assembly and cause sand and shot to be propelled out laterally as shrapnel. This shrapnel could be a significant risk to surface personnel as well as the inflatable boats used by some divers and to divers close to an A.R.D. exploding underwater. Therefore, the A.R.D. was tested on dry land and underwater under the supervision of Explosive Ordnance Disposal (EOD) personnel at the EOD Test Range near NEDU.

II. METHODS

A. Unmanned and Manned Evaluation of the Effects of the A.R.D. on Divers' Hearing

The Naval Coastal Systems Center (NCSC) in Panama City, FL permitted use of the Acoustic Test Facility (ATF) for both unmanned and manned testing of the A.R.D. The A.T.F. is a 6.1m (20 ft) deep fresh water pond at 23.8°C (75°F) water temperature with a centrally placed pool liner allowing both filtration and chlorination of the acoustic test pool area. The gantry and walkways were structurally outside the pool area reducing noise artifact. In both unmanned and manned testing of the A.R.D., one wide band tourmaline hydrophone was used to record the impulse on a magentic floppy disk. A Celesco hydrophone (Model LC-10, Canoga Park, CA) was used to trigger the recording equipment. During manned testing, these microphones were adjacent to the divers' head, away from any exhaled bubbles. The SPL was immediately measured and frequency spectral analysis was performed by storing the waveform of the impulse on a storage oscilloscope (Nicolet Model 4094, Madison, WI). This frequency information was later analyzed by transferring the Nicolet floppy disk data to a Hewlett Packard computer (Model 320, Corvallis, OR) and by using a WaveTek Function Generator (Model 275, San Diego, CA). The frequency spectral analysis was generated by fast fourier transformation (FFT) using a Hewlett Packard (Model HP 3561A) Signal Analyzer. The purpose of such rigorous frequency analysis was to determine any high SPL frequency peaks to help anticipate any effects on hearing as determined by audiometric testing.

All A.R.D.s were exploded at the same depth being held constant at 4m (13.1 ft) by weighted lines to acoustically avoid the thermocline at approximately 3m (9.8 ft). Hydrophones and the divers' heads were also maintained at a constant depth of 4m (13.1 ft). Due to the initial long distance (19m, 62.3 ft) from the exploding A.R.D.s, the A.R.D.s were fired outside the pool liner in the pond water, with the diver inside the pool liner. Preliminary tests verified that the pool liner did not alter the SPL or the frequency spectral analysis of these shots. Furthermore, orientation of the A.R.D. underwater did not influence peak SPL or frequency spectrum of the A.R.D. impulse.

Five male U.S. Navy divers with ages ranging from 26 to 36 were used as subjects following audiological screening and giving informed consent. All five had recently completed another acoustic study in which each diver demonstrated highly reproducible audiograms and hearing in the normal range of sensitivity. Prior to this study, a fatiguer stimulus test (8) was performed on the left ear of each subject to screen for the degree of hearing sensitivity to impulse noise. The fatiguer test is a 5 min exposure to a 3 kHz stimulus at 100 dB with a comparison of the pre-exposure hearing threshold to any temporary threshold shift (TTS) in the audiogram seen at one half octave higher than 3 kHz, i.e. 4 kHz at both one and five minutes after the 3 kHz stimulus (8). Four kHz (4000 Hz) is the frequency where the maximum reduction in hearing sensitivity would be expected from broadband impulse noise.

B. Measurement of Sound Underwater

Sound is measured with sound pressure level (SPL) measured in decibels (dB). SPL is actually a logarithmic ratio of the measured sound pressure (Pm) divided by reference sound pressure (Pref) in equation [1].

$$SPL(dB) = 20 \log (Pm/Pref) \qquad [1]$$

In air, Pref is 20 micropascals (20 uPa) sound pressure which is also equivalent to 0.0002 $dyne/cm^2$ sound pressure. In water, the usual reference is 1 uPa sound pressure. However, with only air impulse noise research and standards to follow due to a lack of research in underwater impulse noise, our underwater SPLs were referenced to 20 uPa (re 20 uPa) based on 20 x log (20/1) = 26 dB, in equation [2].

$$SPL_{water} \text{ (re 1 uPa)} - 26 \text{ dB} = SPL_{water} \text{ (re 20 uPa)} \qquad [2]$$

U.S. Navy Instruction [OPNAVINST 5100.23B, 18103a.(4)] (4) defines hazardous noise as sound pressure <u>in air</u> in excess of 140 dB (re 20 uPa). Therefore, in order to convert SPL in water (SPL_{water} re 20 uPa) to an equivalent sound pressure level in air (SPL_{air} re 20 uPa), one must correct for the density of water (p) and velocity of sound (c) in order to calculate the impedance of water (Z) based on equations [3] and [4].

$$p \cdot c = Z \qquad [3]$$

$$SPL_{air} \text{ (re 20 uPa)} = (SPL_{water})^2/Z \qquad [4]$$

To correct for the impedance difference in water and air, use equation [5] below which subtracts 35 dB from SPL_{water} to give SPL_{air} (3, 19).

$$SPL_{water} \text{ (re 20 uPa)} - 35 \text{ dB} = SPL_{air} \text{ (re 20 uPa)} \qquad [5]$$

Thus, 175 dB (re 20 uPa) <u>in-water</u> equals 140 dB (re 20 uPa) <u>in-air</u>.

In a recent study using an impulse noise producing underwater tool that operates using a gun-powder actuated mechanism, 185.4 dB (re 20 uPa) was recorded at the divers' head (3). Based on equation [5] above, this is equivalent to 150.4 dB in-air (re 20 uPa) which is 10.4 dB above the hazardous limit of 140 dB set forth by U.S. Navy Instruction (4). However, despite as many as 40 consecutive shots fired underwater, no acoustic damage to divers' hearing was demonstrated. Based on these findings, manned testing initially began at a safe distance producing 175 dB underwater, which was equivalent to the current 140 dB in-air hazardous exposure limit. The A.R.D. was then moved closer, by increments of 3 dB, until a level of 185.4 dB underwater was reached, matching the exposure found safe to divers in the recent underwater tool project (3).

By initial unmanned firing of the A.R.D. at 1m (3.3 ft), producing nearly 204 dB (re 20 uPa), the distance to produce 175 dB was found to be 25m (82.0 ft). However, due to size limitations of the test pond, we could only conduct unmanned and manned testing out to 19m (62.3 ft) which was both calculated and observed to give 177 dB of SPL. Therefore, our first manned exposures were done at this distance. After determining that the frequency of the A.R.D. was primarily in the 200-300 Hz range, we knew that the A.R.D. would not be damaging to the lungs of divers. From animal research (12) the natural oscillation frequency of lung tissue is about 50 Hz, which is far enough below the 200-300 Hz frequency of the A.R.D.

The criteria for safety of an unprotected swimmer exposed to an underwater blast takes into account both SPL in psi and duration in msec. These guidelines state that exposure to impulse noise must be less than or equal to 2 psi•msec and the peak over pressure must be less than or equal to a SPL of 100 psi (5, 6). It is also believed that an unprotected swimmer could possibly tolerate up to 10 psi•msec, but animal research has demonstrated minor small blood vessel damage (petechial hemorrhage) in the lungs and gastro-intestinal tract (6). These injuries were not considered life threatening in the research animals and were determined to be acceptable minor injuries to divers under some operational conditions (6). However, for our study, 2 psi•msec was used as the maximum exposure for our divers.

To convert a SPL in dB to units of psi, the following equation, #6, is used according to Zimmerman and Lavine, 1955 (13).

$$\text{psi} = \text{Antilog}\left[(\text{SPL re 20 uPa} + 26)/20\right] \times 1.45 \times 10^{-10} \qquad [6]$$

The literature describing the positive deflection of the impulse known as the A Impulse explains how the area under the A Impulse waveform can be approximated using Friedlander equation [7] below (17, 18).

$$[\text{Pressure (PSI)} \times \text{Duration of A Impulse (msec)}]/\text{exponent } e \text{ or } 2.718 = \text{Impulse (PSI}\bullet\text{msec)} \qquad [7]$$

With a SPL of 185.5 dB equal to 5.44 PSI based on equation (6) and a typical duration of an A.R.D. impulse of 1 msec, the impulse calculates to be 2 PSI•msec based on equation [7].

Based on our unmanned testing, the impulse at 7m (22.9 ft) which lasted 1.0 msec produced 185.5 dB. This is also nearly the value for the recently evaluated underwater, gun-powder actuated tool which produced 185.4 dB. This level of impulse noise was also proven not to cause any acoustic damage to five diver-subjects (3). Therefore, the minimum distance the diver-subjects were allowed to be from the A.R.D. was calculated to be 7m (22.9 ft), equivalent to 2 psi•msec.

C. Audiometric Evaluation

Each diver-subject's baseline audiogram was determined by averaging 14 audiograms done before commencing any exposures to the A.R.D. As defined by U.S. Navy Instruction (4), a significant temporary threshold shift (TTS) was defined as a change of 15 dB from the persons baseline audiogram. This level of significance was followed for the present study.

Audiograms were performed in a portable audiogram booth with a certified audiometric technician using an automated microprocessor audiogram machine (Tracor Corp., Austin, TX). The audiogram booth was sound tested in its location of use and found to be within specifications for conducting audiograms in accordance with American National Standards Institute (ANSI) standard S3.6-1969 and Naval Medical Command Instruction (NAVMEDCOMINST 6260.5).

All subjects were instructed not to use music headphones, or be around loud machinery or noisy public places during the study. Prior to each dive, the subjects were asked if they had any symptoms of difficulty hearing, tinnitus or any exposure to loud noise. The tympanic membranes were thoroughly examined using an otoscope before and after every dive.

The diver was exposed to three A.R.D.s in rapid succession, which is the most expected in a typical diver recall message. Following the post-dive audiogram which was within 3 mins of exposure to the A.R.D., the subject was asked if he had any sensations of fullness in the ears, tinnitus, dizziness, pain in the ears or any rotational movement or any chest or abdominal discomfort of the eyes following the three A.R.D.s fired. Follow-up audiograms were made at two hours following completion of the dive due to the reported delays in the TTS seen following impulse noise exposure (14 and Appendix G of 15).

Standard U.S. Navy diving procedures, according to the U.S. Navy Diving Manual, 1985 (9), were followed with the diver-subject tethered to a surface tender. A fully dressed standby diver topside was immediately available in case of emergency. All personnel received training in the use of the A.R.D. The following emergency procedures were rehearsed; injured diver with mechanical injury, unconscious diver on the surface and underwater, topside abort, diver abort, and A.R.D. misfire (10).

Communications with the diver was with line pull signals. Prior to the firing of the A.R.D.s, the recording gear was turned on and the diver was notified that the A.R.D. would be ignited. The diver was in the vertical position and faced the A.R.D.

If there was any post-exposure audiogram showing a TTS above 20-25 dB, repeat audiograms were to be done a indicated by the Test Director. No diver was allowed to be exposed to an A.R.D. unless his audiogram returned to within 5 dB of his baseline, control audiogram. Manned testing was approved by the diver-subject Human Experimentation Committee at NCSC.

D. Off-Shore Evaluation of Maximum Distance to Hear A.R.D. Underwater

Simultaneously, all five diver-subjects held onto the descent line so that their heads were at a depth of 3m (10 ft) in an open ocean area that was 9.14m (30 ft) deep. To produce the noisiest and most acoustically muffled situation at sea, each diver wore a wet suit hood and breathed from open-circuit SCUBA. One A.R.D. was exploded in the water, without warning to the diver-subjects, by igniting the fuse and immediately dropping it overboard according to the manufacturer's instructions. The distance started at 91.4m (100 yds) and was progressively increased by 91.4m (100 yds) increments to 914.4m (1000 yds). Thereafter, 45.7m (50 yds) increments were used to a maximum distance of 1188.7m (1300 yds). There were no distracting noises from harbor traffic or heavy machinery. No audiograms were needed during this phase of the project.

E. Determination of Shrapnel Risk from the A.R.D.

(1) Dry Land Testing

The A.R.D. was positioned horizontally two feet off the ground using a 2" x 4" soft pine wooden board to hold only the handle of the A.R.D. This allowed nearly a full 360° exposure for shrapnel to be discharged. A circular perimeter of heavy gauge plastic (visqueer, 0.006 inches thick) supported by 2" x 4" boards surrounded the A.R.D. by approximately a four foot radius. This acted to document any shrapnel pieces exploding from the A.R.D. A 100 yd long lanyard allowed the A.R.D. to be fired from a safe distance.

The explosive end of the A.R.D. is capped by a thickness of 0.8 cm of hardened glue and cardboard. To document whether this piece acts as a bullet, shooting straight out the A.R.D., the A.R.D. was fired over a pond. This was to safely witness the end cap landing on the calm waters of the pond. The A.R.D. was positioned at the pond's edge at a 45° angle and surrounded by sandbags allowing only the end cap to act as shrapnel. Even though this sandbagging acted to tamp the A.R.D., it was felt to be the safest and most reliable way to test for end cap shrapnel.

(2) Underwater Testing

Since high velocity shrapnel may injure a nearby diver, the A.R.D. was tested underwater. A plastic bucket was submerged underwater and an A.R.D. was suspended in the center of the bucket after igniting the fuse. The bucket was then re-examined for evidence of imbedded shrapnel. Previous dry land testing of one unlighted A.R.D. taped to an ignited A.R.D. demonstrated to NSWC that there is no sympathetic ignition risk (2). However, this has not been done underwater. We therefore taped two A.R.D.s together and after igniting only one fuse threw both into the water. If the second A.R.D. did not explode sympathetically it was intended to attempt to ignite it after immersion underwater for another 30 sec.

It is also possible that immersion of an A.R.D. will flood the fuse assembly and prevent it from being ignited. A.R.D.s were therefore pre-immersed for two min before attempting to ignite the fuse.

All dry land and underwater testing was rigorously controlled for safety. An EOD representative supervised all testing, using standard EOD procedures and VHF radio communications.

III. RESULTS

A. Pre-dive Audiometric Evaluation

Table 1 demonstrates hearing within the normal range of sensitivity according to Ward, 1963 (8).

TABLE 1

AUDIOGRAM AT 4 kHz (dB)

Subject	Pre-Fatiguer	Post-Fatiguer 1 Min	(Change)	5 Min	(Change)
T.K.	40	64	(24)	54	(14)
M.G.	36	55	(19)	50	(14)
S.P.	30	47	(17)	40	(10)
S.S.	30	46	(16)	40	(10)
J.N.	34	55	(21)	48	(14)
Mean ± S.D.	34.0 ± 4.2	53.4 ± 7.3	(19.4±3.2)	46.4 ± 6.2	(12.4±2.2)

Results of Fatiguer Stimulation Test. Stimulus was 100 dB at 3 kHz for 5 min in the left ear, n=5 subjects. Pre- and post-fatiguer hearing thresholds were measured at 4 kHz with post-fatiguer hearing threshold measured at 1 and 5 min. Comparison of pre and post-fatiguer hearing thresholds shown as (change). Mean ± S.D.

In Table 2, the baseline audiograms for all five divers are shown.

TABLE 2

LEFT EAR(Hz)

SUBJECT	500	1K	2K	3K	4K	6K	8K
TK	6.7(5) ± 2.4	10.0(10) ± 0	17.[illegible](15) ± 2.5	15.7(15) ± 2.6	22.1(20) ± 2.5	27.1(25) ± 3.2	19.6(20) ± 2.3
MG	10.7(10) ± 2.6	18.9(20) ± 2.1	10.0(15) ± 0	14.6(20) ± 3.0	18.5(20) ± 3.0	23.5(25) ± 6.0	23.5(25) ± 4.9
SP	3.2(5) ± 3.1	-2.8(-5) ± 2.5	0.3(0) ± 1.3	1.4(0) ± 2.2	5.0(5) ± 1.9	9.6(10) ± 3.6	5.7(5) ± 4.3
SS	9.6(10) ± 4.1	6.7(5) ± 6.7	-0.3(0) ± 3.6	12.5(15) ± 3.7	11.4(10) ± 4.1	20.7(20) ± 3.3	15.7(15) ± 3.3
MW	4.0(5) ± 2.2	-1.0(0) ± 2.2	-4.0(-5) ± 2.2	-2.0(0) ± 2.7	1.0(0) ± 2.2	5.0(5.0)± 0.0	1.0(0) ± 6.6

RIGHT EAR(Hz)

SUBJECT	500	1K	2K	3K	4K	6K	8K
TK	3.9(5) ± 3.0	5.0(5) ± 0	21.0(20) ± 2.8	10.7(10) ± 1.3	19.6(20) ± 1.3	22.1(20) ± 4.6	12.8(15) ± 4.7
MG	13.9(15) ± 2.8	18.2(20) ± 3.1	7.5(10) ± 3.2	6.7(5) ± 2.4	18.9(20) ± 2.1	16.7(15) ± 6.9	25.0(25) ± 5.5
SP	2.8(5) ± 5.4	10.7(10) ± 5.4	5.3(5) ± 4.5	8.9(10) ± 5.2	2.1(0) ± 3.1	21.7(20) ± 5.7	10(10) ± 8.3
SS	6.7(5) ± 2.4	4.6(5) ± 3.6	-2.1(0) ± 2.5	1.4(0) ± 2.3	-0.3(0) ± 2.3	9.6(10) ± 3.0	8.9(10) ± 2.9
MW	6.0(5.0)± 2.2	2.0(0) ± 2.7	5.0(5) ± 0	6.0(5) ± 2.2	4.0(5) ± 2.2	5.0(5) ± 3.5	6.0(5) ± 4.2

TABLE 2. Baseline audiograms for Left and Right ears for each of five experimental subjects; mean ± SD and rounded value (dB) rounded to increments of 5 dB in parentheses, n=14 audiograms.

B. Unmanned A.R.D. Evaluation

Table 3 illustrates unmanned testing SPL values:

TABLE 3

Distance (m)	SPL (re 20 uPa)±S.D.,(n value)
1.0	203.8 ± 1.63, (n=9)
7.0	185.5 ± 0.75, (n=5)
9.4	183.3 ± 1.54, (n=4)
10.0	182.0 ± 1.21, (n=8)
13.0	179.2 ± 0.51, (n=3)
19.0	175.5 ± 0.95, (n=3)

C. Manned A.R.D. Evaluation

Table 4 illustrates manned testing SPL values.

TABLE 4

Distance (m)	SPL (re 20 uPa)±S.D.,(n value)
7.0	186.2 ± 1.79, (n=8)
8.5	184.4 ± 1.54, (n=7)
12.0	180.8 ± 1.36, (n=7)
17.0	177.2 ± 1.34, (n=5)
19.0	177.2 ± 1.21, (n=10)

The FFT analysis of the A.R.D. positive waveform impulse demonstrated a relatively broad band of noise with the major SPL frequencies between 200-300 hz. If both the positive and the following small negative waveforms are both analyzed, the overall peak SPL frequencies are clustered around 170 Hz.

These frequencies would be expected to produce a TTS on the audiogram approximately 1/2 octave higher which would be demonstrated at the 500 Hz level on the audiogram. However, we never demonstrated any significant TTS as close as 7m (22.9 ft) in any of the five diver-subjects either immediately after A.R.D. exposure or two hours later. All subjects described the 186.2 dB peak SPL at 7m (22.9 ft) as very loud, frequently causing an involuntary contraction of their anal sphincter muscles. Also, their eyes would blink and

their face masks would be compressed sharply on their face. There was no uncomfortable sensations in the chest, similar to what has been described with much lower frequency TNT explosions underwater. No divers had any fullness, tinnitus or pain in their ears, nor did they have any gastrointestinal symptoms. The otological exam of the tympanic membrane was also normal for all subjects following exposure to the A.R.D.s.

D. Off-Shore Evaluation of Maximum Distance to Hear the A.R.D.

Wearing wet suit hoods, all five divers reproducibly heard the A.R.D.s to a distance of 1006m (1100 yds). A few divers could reproducibly hear the A.R.D. as far as 1143m (1250 yds).

Overall, 235 A.R.D.s were tested with no misfires or improperly functioning fuses.

E. Shrapnel Risk Evaluation

In surface testing of the A.R.D., extensive shrapnel fragmentation from the cardboard and plastic housing occurred nearly 360° around the A.R.D. Sand and lead shot primarily exploded laterally and behind the A.R.D. as predicted. All fragments including sand and lead shot easily penetrated the heavy plastic perimeter and were found imbedded into the soft pine 2" x 4" posts. Pieces of cardboard and hot melt glue were found up to 50m (164 ft) away. The solid glue and cardboard end cap was propelled straight out the A.R.D., curving off to either side, landing as far away as 50 to 60m (164 to 197 ft). Underwater tests demonstrated pieces of the A.R.D. housing and a metal fragment embedded into the torn plastic of the underwater bucket.

Sympathetic testing did not initiate the unlighted A.R.D. which was heavily damaged. Despite significant damage, though, the second A.R.D. was able to be ignited using the fuse even though it was left underwater up to two min after the first detonation. After pre-soaking four A.R.D.s underwater for two min only two of them could be ignited and exploded.

IV. DISCUSSION

This study empirically demonstrated that man can tolerate three rapid impulses, each up to 186.2 dB (re 20 uPa) in-water without any evidence of hearing damage. This reconfirms our earlier study demonstrating no effect on hearing from underwater exposure to 185.4 dB (re 20 uPa) in-water from an underwater tool (3). The conversion of 186.2 dB in-water in this study to an equivalent value of 151.2 dB in-air is valid and represents 11.2 dB above the current safe exposure limit to impulse noise in-air (4). However, still very little is known about the mechanism(s) of underwater hearing in man. In a recent review of underwater hearing in man (16), Smith very thoroughly reviewed the current theories of underwater hearing including both the bone conduction and tympanic membrane pathways of hearing. However, further

research is needed to understand underwater hearing before predictive modeling can help to determine safe exposure limits based not only upon SPL and impulse duration, but also the frequencies of underwater noise that may be most harmful to man's hearing.

The A.R.D. minimum safe distance was predetermined to be 7m (22.9 ft) by both unmanned testing and current standards for exposure to an underwater blast (5, 6) and also verified medically safe by manned testing. The reliable maximum distance for all five diver-subjects to reproducibly hear the A.R.D. in open water of approximately 10m (32.8 ft) depth in the absence of any distracting harbor noises was determined to be 1006m (1100 yds). However, the shrapnel risk of this device on the surface and potentially underwater to the nearby diver is very severe. The amount of explosives can probably be reduced and the materials be relocated to move any potential shrapnel away from the explosive to greatly improve the safety of this recall device. An air containing resonator near the explosive section similar to the Canadian Thunderflash diver recall device could remove the lead ballast away from the explosive charge.

It certainly is possible that someone will drop a lighted A.R.D. while on-board a rolling inflatable boat or mischievously toss an A.R.D. near someone on the surface, resulting in damage to the boat or severe injuries to personnel. Therefore, based on the results of this study, this A.R.D. was determined to be hazardous.

One potentially serious theoretical risk not addressed is the effect of such a strong impulse on a diver decompressing or near the no-decompression limits. The pressure wave traveling through the diver's tissues may precipitate decompression sickness by coalescing asymptomatic small bubbles into larger bubbles or even nucleating new bubble formation by cavitation of super saturated tissues. Presently, no research exists to support or refute this serious possibility.

V. CONCLUSION

The A.R.D. was demonstrated not to cause any acoustic, pulmonary or gastrointestinal damage to divers as close as 7m (22.9 ft) from this underwater explosion. Severe shrapnel risk exists making this recall device very hazardous. A short period of water immersion will render some A.R.D.'s unusable. Changes which could improve the safety of this device include reducing the amount of explosive, and moving the explosive section farther from potential shrapnel, possibly by using an air containing resonator section between the explosive and the ballast.

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